Adaptive Multi Charge Ignition for Critical Combustion Conditions

Modern spray-guided combustion concepts have substantially raised the requirements for ignition systems due to the short time intervals between injection and ignition combined with the highly varying mixture concentrations close to the spark plug. This paper presents Delphi's robust, current-controlled multi charge ignition and shows the application on a stratified fuel combustion concept.

1 Introduction

Spray-guided combustion concepts provide the largest potential of reducing fuel consumption of all individual four-stroke gasoline engine technologies. In order to fully use this potential, despite the relatively short time for mixture preparation, ignition systems must be developed to address the weaknesses of the spray preparation and/or the air/fuel mixture and to reduce the tolerance requirements on components used. The typical approach of high-energy ignition coils has disadvantages regarding cost, weight and packaging. Also it cannot fully meet certain functional requirements, despite high energy and long burn time. The current-controlled multi charge ignition introduced here reduces these disadvantages and opens up a way to smaller and lighter ignition coils.

2 Multi Spark Ignition Systems

Multi spark ignition systems can be divided into time-controlled and current-controlled systems. Time-controlled systems work independently of the respective charge of the coil by applying a charge/discharge pattern according to a fixed map, stored in the engine control unit (ECU). On the other hand, current-controlled systems align the recharging of the coil based on the actual condition of its stored energy. Since the coil discharge-characteristic is considerably influenced by the processes in the combustion chamber, current-controlled systems can deal better with widely varying conditions. A special form of a multi spark ignition system, alternating current ignition (AC-Ignition), is not being discussed here [1]. Due to its cost disadvantages it is found only in a few luxury vehicle applications.

2.1 Time-controlled Multi Spark Ignition

Such systems, also known as spark-train ignition, are charged several times per engine cycle by the ECU (open loop). Two modes of operation can be differentiated:

– Recharging only after a complete coil discharge, **Figure 1** (a): In this system, varying initial conditions which are unknown by the ECU at the time of recharge are avoided. However, the time to the next spark increases. Meaningful repetition rates are only achieved for low engine speeds, as for instance during engine start. At 1000 rpm for instance, a delay between sparks of 6 ms corresponds to 36 ° crank angle. Obviously the second spark is already so far away from the optimal ignition set point that a misfire may still be prevented, but the ef-

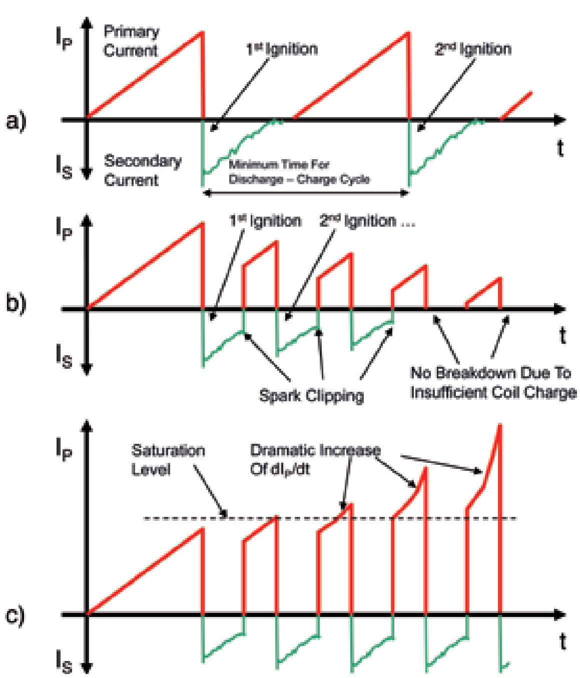

Figure 1: Time controlled multi spark ignition: a) uninterrupted individual sparks; b), c) using "Spark Clipping", case low battery and high battery voltage, respectively

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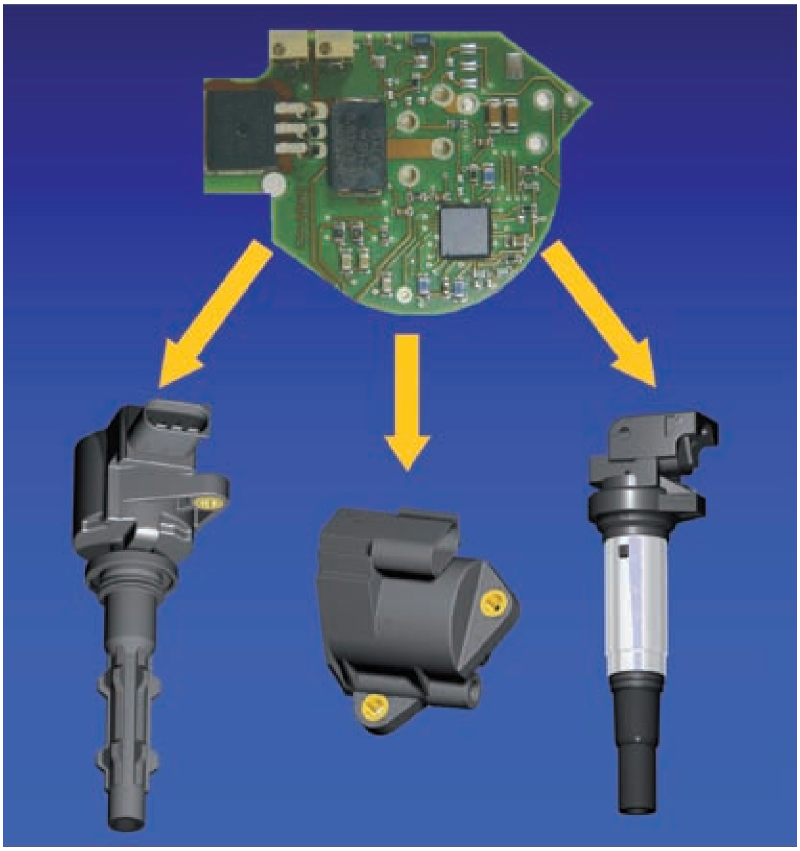

Figure 2: Different coil designs (plug top coil, coil near plug, pencil coil) with integrated multi charge ignition electronics (MCI)

fect is essentially limited to an engine-internal HC reduction.

- Recharging by interruption of the spark („spark clipping“): The spark repeat rate rises, however the ECU is unaware of the remaining coil charge level at the beginning of the recharge. A high rate of energy discharge from the coil or, for example a low battery voltage during the recharge leads to a low-charge status, Figure 1 (b). The coil cannot ensure ignition any longer. In the contrasting case, Figure 1 (c), coils can be overcharged and driven into magnetic saturation. The high current arising from this condition can damage the coil or the driver.

2.2 Current- and Demand-controlled Multi Charge Ignition

In contrast to the time-controlled method, the Delphi multi charge ignition system (MCI) uses a current feedback (closed loop) for both primary charge current and secondary discharge current. The energy content of the coil is thus monitored at all times [2]. In the year 2000 Delphi had already developed an ignition system that generated a very robust ion current signal to assess the combustion quality. The multi charge algorithm implemented in that application already featured a primary and a secondary current control. The same algorithm has been implemented in the multi charge ignition system described here. The Delphi MCI system does not require a radically different coil design. Pencil coils, plug top coils or near plug coils, mounted inside or outside the plug-well can be used, **Figure 2**.

2.2.1 Ignition Coil Design

Two substantial requirements for the MCI system are impacting the transformer design of the ignition coil:

- High Secondary Voltage Capability. If the coil cannot supply the high voltage necessary for the breakdown of the gap, for instance between wet electrodes, a misfire results. In order to fulfil the requirement for a high secondary voltage capability, the parasitic secondary capacitance especially of small coils must be minimized by design.
- Fast Recharge. At high burn voltages the spark extinguishes quickly because of the fast coil discharge. In order to be able to ignite again within the shortest time with full power, the primary winding is designed with very low resistance and inductance, so that a full charge can easily take place in less than 1 ms.

2.2.2 Coil-integrated Electronics

Figure 2, above, shows the printed circuit board that is being integrated in the coil. The ignition IGBT (Insulated Gate Bipolar Transistor) and an integrated circuit (ASIC), responsible for the execution of the multi charge ignition algorithm can be seen. The ASIC is packaged with Flip Chip technology to minimize its footprint and contains all further functions necessary for autonomous operation.

2.2.3 Functional Description

When the first discharge of a MCI coil is controlled with an engine spark timing signal, then subsequent ignition cycles automatically start for a selected algorithm. **Figure 3** demonstrates the principle using a 10 mm wide spark gap with air injection. The photo, taken with an open shutter, shows the impressive deflection of the spark. The individual plasma threads belong to the discharges that successively follow each other. The first breakdown corresponds with the lowest displayed plasma thread which is produced across the shortest way between the electrodes, while the later ignitions belong to spark channels extending further out. The shown multi charge cycle is with approximately 20 discharges about 5 ms long and delivers a total energy of approximately 200 mJ. The upper curve in Figure 3, top right, shows the secondary voltage U_S and that with increasing spark deflection also increasing break-down voltage U_Z. Below is the secondary current I_S followed by the primary current I_P.

The close-up in Figure 3 bottom is used to explain the MCI control algorithm and the available calibration parameters.

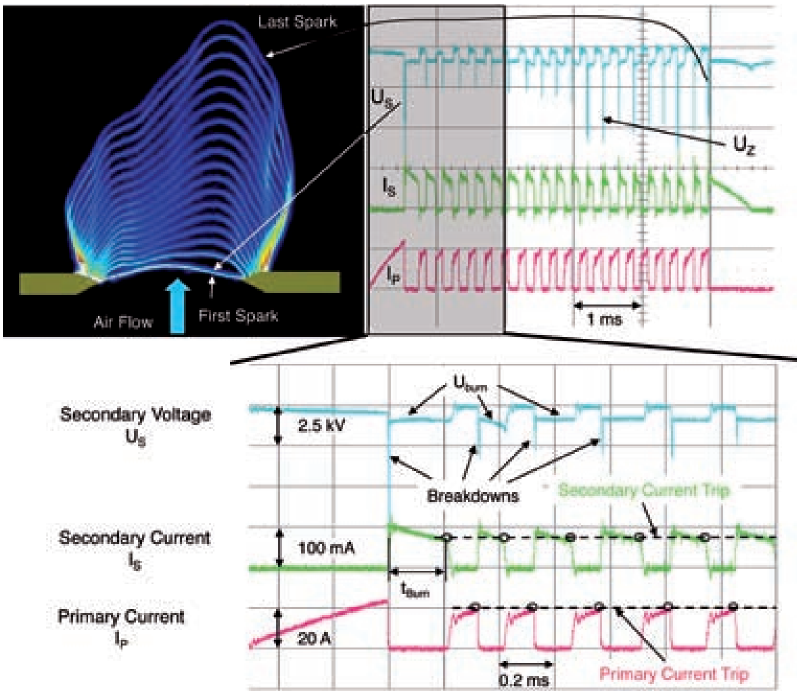

Figure 3: Multi charge ignition, definitions and functioning principle

2.2.4 Interface to Engine Control Unit, Initial Charge

The interface of the MCI system to the ECU uses a typical engine spark timing signal. Its length determines the charge duration and its falling edge the desired time of ignition, spark advance (SA), and is thus compatible to existing engine control systems.

2.2.5 Secondary Current Trip

At the falling edge of the engine spark timing signal a breakdown of the gap occurs, Figure 3 bottom, blue curve, and the spark begins to burn with the secondary current I_S (green). While burning, the MCI system is constantly monitoring the secondary current and interrupts the spark when an adjustable threshold value is reached (secondary current trip) in order to recharge the primary coil again. Spark energy and burn time t_{Burn} implicitly set by this threshold, depend on the respective thermodynamic conditions in the combustion chamber.

2.2.6 Primary Current Trip

After the interruption of the spark current I_S the coil is recharged. The primary current I_P , Figure 3, red curves, starts with the current that corresponds to the residual charge in the coil. During coil recharge, the system is now monitoring the primary current. The recharging continues until I_P has reached an adjustable threshold (primary current trip). Then a new ignition event takes place. The adjustable current threshold for the coil recharge can be set independently from the current value of the initial charge by engine spark timing signal.

2.2.7 Length of the Multi Charge Ignition Cycle

The sparking duration of the Multi charge ignition cycle can be set by the ECU up to a maximum length of 40 ° of crank angle (°CA). In operating conditions during which repetitive ignition is not necessary, such as during longer fuel cut-off periods or out-side the stratified operating range, the length of the MCI cycle can be shortened accordingly.

3 Ignition of Stratified Charges

Spray-guided combustion systems make very high demands on an ignition system in the stratified operation area. Air-fuel ratio and in-cylinder flow speed of the mixture in the proximity of the spark plug vary over a wide range. Other variables with strong influence are the spray pattern and the tolerances of the injectors, as well as the cyclic fluctuations induced by the gas exchange. For example, according to the findings of Paschen, [3], the breakdown voltage U_Z steadily increases as a function of the gas density,

Combustion System	Spray - Guided
Injector Position	central, 0 tilted
Spark Plug Position	Off center in crankshaft axis, 28 tilted
Piston	moderate central bowl
Compression Ratio	11.7
Injector	Outwardly opening, single coil actuator
Spark Plug	NGK T20023L
Test Fuel	Shell V Power

Single Cylinder Engine	
Displacement [ccm]	499
Bore [mm] / Stroke [mm]	86 / 86
Conrod length [mm]	143
Number of Valves	4
Valve Angle [ ] IV / EV	23 / 23
Intake Opening	34 b TDC
Intake Closure	54 a BDC
Exhaust Opening	74 b BDC
Exhaust Closure	14 a TDC

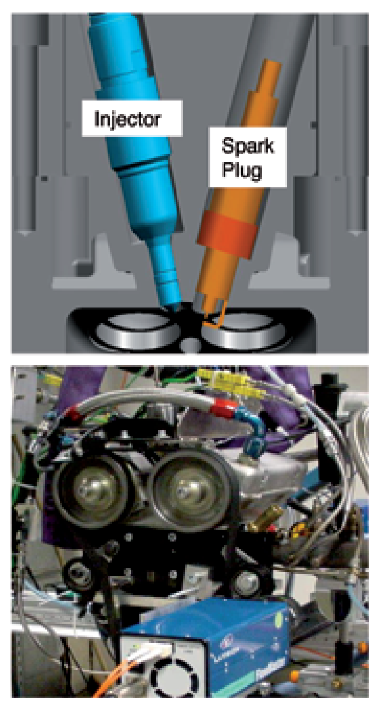

Figure 4: Research engine specification

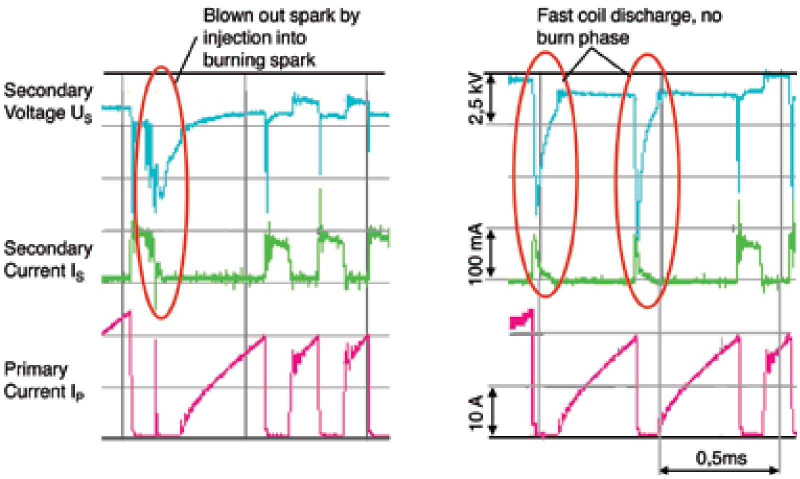

Figure 5: Misfire conditions leading to fast coil discharge

i.e. the pressure p, and the spark plug gap d. By using a MCI system the subsequent ignitions can lie in the proximity of the ignition top dead centre ITDC and thus encounter higher pressures. This generally leads to higher averages of breakdown voltage than in the case of single charge ignition systems in the same engine. Short mixture preparation times and thus an inevitable amount of liquid fuel within the range of the plug or fuel deposits on the electrodes likewise require higher breakdown voltages. Additionally, the high thermal capacity of liquid fuel makes it even more difficult for the ignition to initiate a flame front, since the liquid phase is cooling the plasma channel after the breakdown.

Apart from the in-cylinder flow and turbulences generated during gas exchange, the injection cycle itself produces additional flow patterns. Due to the small temporal and local distance to the spark plug gap, this all can have effects on the spark. In order to achieve an as stable an ignition as possible, sufficiently long burn time and a high degree of immunity against extinguishing the spark by the high flow velocities dominant in the boundary region of the spray must be fulfilled as boundary conditions. Today's single spark ignition systems with energies around 100 mJ are fulfilling these requirements only conditionally. If a single spark is extinguished, then a coil already partially discharged has only a limited ability to re-ignite.

On the other hand the MCI system described here is appropriate for a system-inherent safe re-ignition. It uses recharging times down to 100 µs, during which the plasma thread of the just interrupted spark hardly cools down. However the hot gases are moving away from the plug gap by so-called entrainment flow [4]. Thus the former still-hot spark channel provides an attractive path for the next breakdown, so that the arc can follow the flow.

4 Test Results on a Single-cylinder Engine Operated in Stratified Mode

4.1 Research Engine

A single-cylinder research engine has served as a test engine. The combustion chamber geometry was designed at Delphi for the development of fuel stratified injection systems. A Delphi-developed, outwardly opening injector with single solenoid coil drive is used [5]. **Figure 4** shows the essential geometry data of the engine and its combustion chamber. The engine dynamometer is fully automated and equipped with complete exhaust analysis facilities. All operating media are conditioned.

4.2 Engine Results

The engine runs in fuel stratified operation with a single injection, 50 mbar vacuum in the intake and without external exhaust gas recirculation. The pressure indication with subsequent averaging is performed over 750 cycles. A single

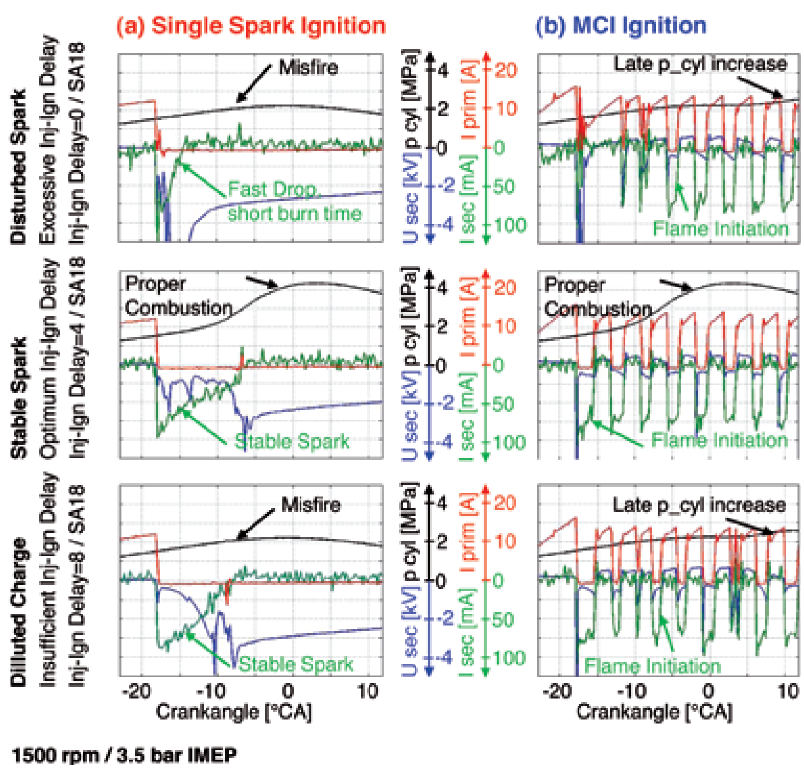

Figure 6: Characteristic electrical signals of the ignition coil at critical ignition conditions plotted over crank angle – fixed spark advance

charge ignition coil (90 mJ) and the Delphi multi charge ignition system MCI are compared at a representative part load point (1500 rpm / 3.5 bar indicated mean effective pressure IMEP). No difference of the two examined ignition configurations can be determined at homogeneous engine operation. Also, the homogeneous lean burn limit remains essentially unchanged.

4.3 Characteristic Electrical Signals on the Occurrence of Misfires

Figure 5 shows two misfire mechanisms which empty the ignition coil completely. In the picture, left, the injected spray reaches the gap after the breakdown already took place. By the high liquid phase portion the burn voltage rises strongly and the coil empties itself rapidly. After approx. 150 μs the secondary current has dropped to 0 mA and the spark extinguishes.

In the right picture at the desired spark timing no real burn phase can be detected. Instead of a breakdown, U_S shows a curve shape similar to a ring-out. The coil energy is being dissipated in the ohmic resistances of the secondary circuit. Such a case can be observed when the gap electrodes are wetted with fuel or if the high voltage capability of the coil is insufficient.

In both cases a single charge ignition would fail. An only time-controlled multi spark ignition cannot achieve the energy level necessary for a safe ignition due to the „unexpectedly" low residual energy of the coil. The current-controlled MCI system, however, increases the chance of a successful ignition by recharging the completely emptied coil before the next ignition to the pre-defined primary current level.

4.4 Characterisation of Misfires During Stratified Operation

Figure 6 shows for selected cycles the electrical signals of the ignition coil and the cylinder pressure plotted versus the crank angle. The left side shows the behaviour using a single charge ignition (a), the right side represents the MCI system (b). Here, the ignition timing is held constant at 18 ° CA before TDC (in the pictures called Spark Advance, SA18) in order to avoid an influence of the cylinder pressure on the breakdown voltage. The injection timing (End of Injection, EOI) varies from 18 ° CA before TDC (EOI18) over 22 ° CA (the reference) to 26 ° CA.

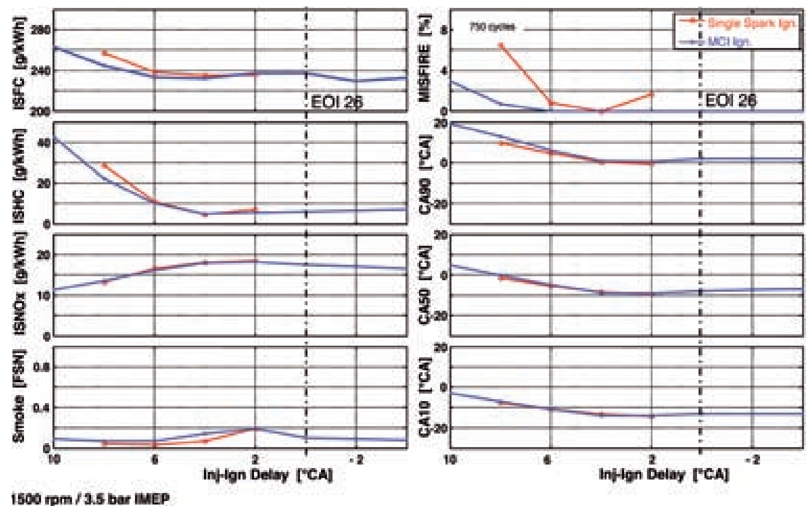

Figure 7: Stratified operation with fixed EOI – single versus multiple ignition

The centre row of the picture array shows a stable, misfire-free combustion initiation and a consecutive burn phase for both ignition systems at optimal settings.

The upper row shows a disturbed spark with insufficient time between injection and ignition. The spray is reaching the plug gap while the arc is already burning which rapidly discharges the coil. Here, the single charge ignition fails. These are so-called rich misfires [6, 8]. On the other hand, the current-controlled MCI system allows certain, albeit retarded ignition by one of the subsequent sparks, identifiable by the trace of the cylinder pressure.

The lower row shows an unimpaired spark with a large time between injection and spark timing. Nevertheless, the single charge ignition cannot ignite the mixture reliably, since at the time of the spark the mixture at the spark plug location is already strongly diluted and quite lean. Due to the high cyclic fluctuations of the in-cylinder flow, this generates periodically so-called lean misfires [6, 7]. The MCI allows again a sure, however, as before, retarded ignition.

4.5 Engine Behaviour in Stratified Mode

In **Figure 7** the ignition timing varies while the end of injection is fixed at EOI26. As expected, no differences can be seen at the operating points in which both ignition systems work misfire-free, either for fuel consumption (ISFC), for emissions (ISHC, $ISNO_x$, Smoke) or for fuel conversion (CA10/50/90 are the degrees of crank angle for 10/50/90 % burned fuel).

In the upper right plot it is evident that the area for misfire-free ignition can be clearly expanded with the MCI system compared to a single charge ignition: If not enough time between EOI and SA is provided, the charge will be insufficiently mixed. Locally rich areas with reduced oxygen entrainment develop and lead to an incomplete combustion with high carbon concentration. MCI is reducing the risk of these rich misfires.

In the case of highly retarded ignition events, lean areas are forming which are difficult to ignite. The MCI system counteracts this situation with extended effective spark duration and a stretched spark which has a higher likelihood to hit combustible mixtures than an individual spark. Consequently, the MCI system leads to lower fuel consumption and HC emissions in areas where lower misfire rates are achieved.

In contrast to the single charge ignition which requires in this operating point an ignition timing of at least approximately 2 ° crank angle after EOI, for the MCI system a highly advanced spark timing can be chosen, far earlier than the arrival of the spray to the plug gap. Due to the arbitrarily adjustable spark duration, the mixture starts to burn safe-

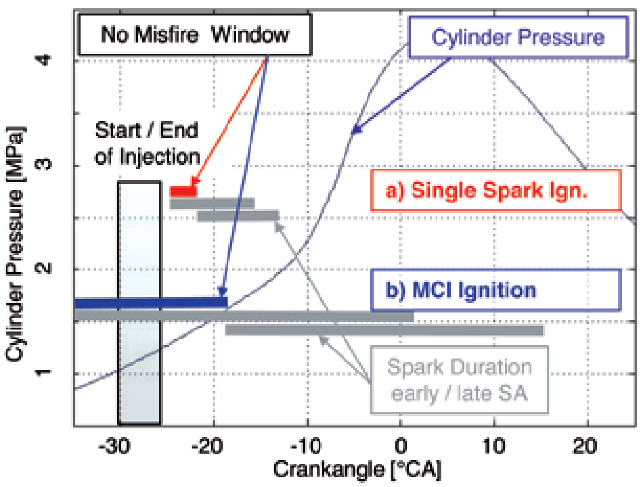

Figure 8: Allocation of injection and ignition in stratified combustion

ly as soon as the ignition conditions are fulfilled.

Figure 8 visualizes the location of injection, ignition and cylinder pressure pattern for the examined operating point. The vertical bar shows the duration of the injection. The upper horizontal bars describe the ignition window for both systems, the two lower bars the extreme values of the approximate spark duration.

In **Figure 9** characteristic diagrams of the important engine output maps are plotted versus the axes “EOI” and “Delay from EOI to spark timing SA”. Results for a single charge ignition (left) and the MCI system (right) are compared.

In the case of the single charge ignition, misfire-free operation is only possible in a narrow injection and ignition area. Due to its relatively early occurrence before TDC it shows increased NO_x emissions. The much broader application window for injection and ignition of the MCI system increases the robustness of the overall system against production-related tolerances of components, e.g. injectors and their spray patterns, as well as against effects of aging, without compromising combustion stability and freedom from misfires. This allows a calibration with retarded injection and ignition timing leading to significantly lowered NO_x emissions as a result of the reduced combustion pressures and temperatures. In addition to the nearly 20 % reduced fuel consumption compared to stoichiometric operation, this leads to fewer regeneration cycles of the $DeNO_x$ catalyst (rich homogeneous operation) and thus to an additional fuel consumption advantage for the MCI system.

5 Summary, Conclusions and Outlook

The current-controlled, fast recharging multi charge ignition system MCI presented here makes available a substantially longer effective spark. The working principle prevents undefined and insufficient charges of the coil, allows a broader deflection of the spark into the combustion chamber and provides several times the full ignition energy in cases of potential misfires.

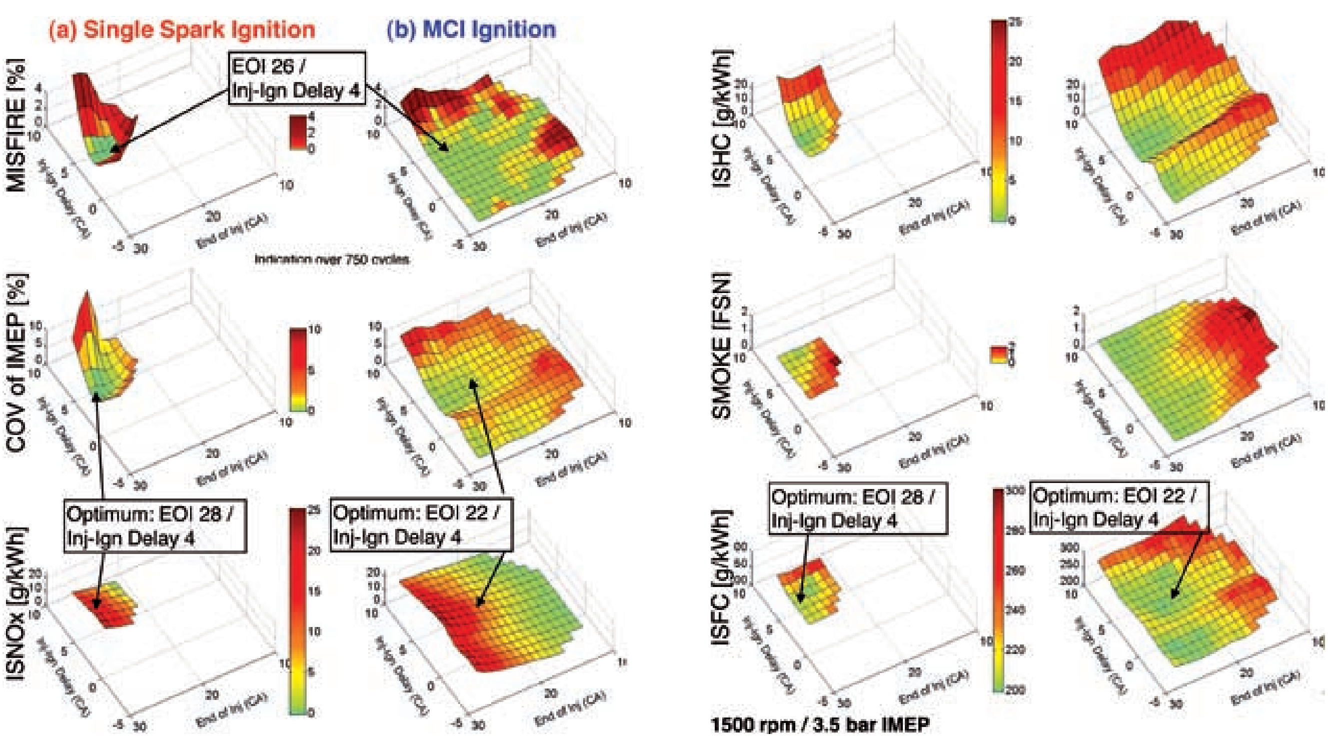

Figure 9: Engine results for stratified operation (1500 rpm / 3.5 bar IMEP)

Extended, misfire-free operating ranges for stratified engine operation can be obtained, which are characterized by improved emissions and a lower fuel consumption. With an engine operated in stratified mode these effects could be proven at a representative speed/load point. The engine results that can be obtained with the MCI system permit a cost optimization of the overall powertrain system in stratified operated engines. This applies in particular to the exhaust aftertreatment system, the cold start performance and the reduction of tolerance requirements of components.

A very robust combustion detection method using ion-current sensing technology is currently being developed. It is based on the concept of the current-controlled multi charge ignition system presented here. This particular ion sense capable system avoids some well-known disadvantages of the ion current ignition systems described in the literature and can be used for combustion control.

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